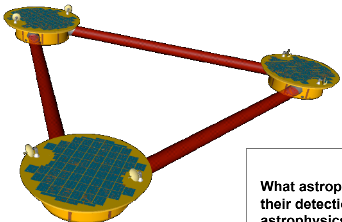
Astrophysics at *z~10* with Gravitational Waves



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Abstract

What astrophysics can be done at redshifts beyond 5 using the gravitational waves? Historically, gravitational wave antennas have been characterized by their detection capability. This is measured in terms of signal-to-noise ratio, and implies a rate of false positives and false negatives. But to do useful astrophysics, one would like to measure – or more properly, estimate – astrophysical parameters of the gravitational wave sources. In the interest of strengthening the connection between science objectives and a specific instrument performance, the LISA community has reformulated the LISA science requirements around the anticipated uncertainty in astrophysical parameter estimation. The rationale for this characterization of LISA and a summary of the astrophysics that LISA can do is given.

Science Performance and Science Requirements

As with other gravitational wave detectors, the performance of LISA has been characterized by the potential sources which it could detect with adequate signal-to-noise ratio (SNR), typically 5 or greater. But if gravitational wave detectors are to become observatories rather than physics experiments, then they are better characterized by their ability to determine astrophysical parameters of potential sources, in particular, by the uncertainties in their measured, or more properly, estimated parameters.

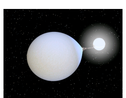
In every space mission, the Science Requirements Document (ScRD) is the foundation for the instrument design and the basis for the anticipated science return. The performance requirements on the instrument are derived from science goals stated in the ScRD and then "flowed-down" through all the levels of subsystems, even to critical components. Not only has LISA performance been characterized by detection sensitivity and SNR, but the current and all previous versions of the ScRD have been based on sensitivity and SNR leading to detection.

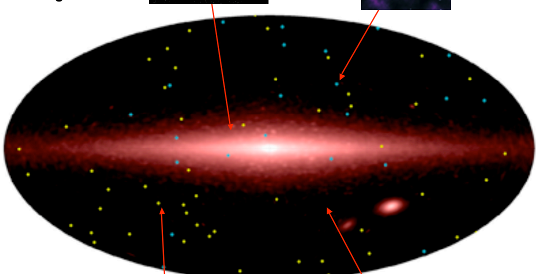
Here, we will characterize LISA's performance based on uncertainties in parameter estimates for the most distant sources, and illustrate how the ScRD is being revised around parameter uncertainties. This novel approach produces a quantitative validation of instrument performance devolved from science objectives, through specific investigations, specific observations and parameter estimation.

LISA Sources

Much effort has gone into assessing what sources the LISA baseline conceptual design can detect. The four classes of detectable sources are shown below in the simulated all-sky map with typical mass range, location and numbers, where known.

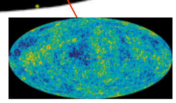
Ultra-compact binaries
- ~1 $M_\odot$
- Galactic and extragalactic
- ~10,000
- Confusion foreground





Extreme mass-ratio inspirals
- ~10/ 10^6 $M_\odot$
- *z < 1*
- 10's - 100 per year

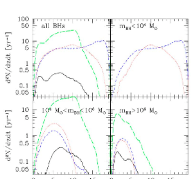
Massive and intermediate-mass black hole binaries
- 10^2 - 10^7 $M_\odot$
- *z < 20*
- 10's to 100 per year



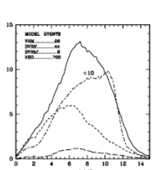
Cosmological back-grounds, bursts and unforeseen sources

The uncertainty in the estimation of source parameters in one of these classes depends on the parameter values intrinsic to the source (masses, spins, eccentricity, separation, orbital phase) and the extrinsic parameters of the observer (luminosity distance, relative geometry, inspiral phase, orbital phase of the detector). A gravitational wave receiver's capability to perform science will have to reflect the ensemble of potential sources in a class.

For illustrative purposes, this poster will focus on the science objective of deducing the merger history of massive black holes, using observations of massive and intermediate-mass black hole binaries. The two plots below from Sesana et al (2004) illustrate hierarchical merger trees for four different assumptions about the "seed" black holes. To fulfill this objective, the detector needs to be able to measure mass and luminosity distance are large redshifts well enough to discriminate between models.

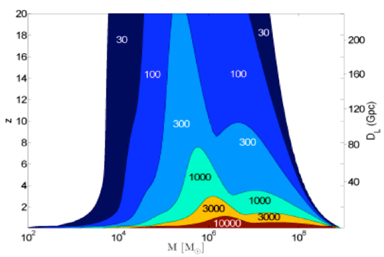


Sesana et al 2004 ApJ, 611, 623



"Detection" vs. "Observation"

"Detection" means:
- Determine the likelihood of a source signal in the data
- Figure of merit is SNR
- Useful, but doesn't answer specific scientific questions, like what is the merger rate of intermediate mass black holes at *z=10*?



The graph to the right shows SNR contours for equal mass binaries versus total system mass and redshift. In the most extreme case, LISA could detect a 10^4 $M_\odot$ black hole falling into a $3x10^4$ $M_\odot$ black hole at *z=30* with *SNR=10*, but with 100% uncertainty in the distance determination.

"Observation" means:
- Estimate the value of source parameters
- Figure of merit is uncertainty in parameter estimate, e.g., luminosity distance, masses, spin parameters, sky location, etc.
- Observation is really the desire metric of scientific capability.

Example of Science Requirements based on Parameter Uncertainties

One of LISA's seven science objectives is: Trace the growth and merger history of massive black holes and their host galaxies. One of three science investigations, and an associated observation, to support that objective is:

Science Investigation

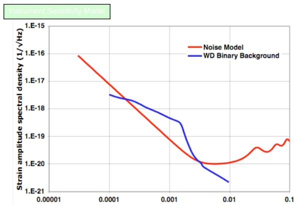
4.2.1 Determine the relative importance of different black hole growth mechanisms as a function of redshift

Observation Requirement

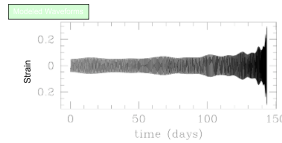
OR2.1: LISA shall have the capability to detect massive black hole binary mergers, with the larger mass in the range $3x10^4\ M_\odot < M_1 < 3x10^5\ M_\odot$, and a smaller mass in the range $10^3\ M_\odot < M_2 < 10^4\ M_\odot$, at $z = 10$, with fractional parameter uncertainties of 25% for luminosity distance, 10% for mass and 10% for spin parameter at maximal spin. LISA shall maintain this detection capability for five years to increase the number of observed events.

The performance of a specific instrument (cf.instrument sensitivity model below) can be assessed by calculating specific (fixed mass and distance) simulated, 2 PN waveforms with randomly chosen sky locations and spin.

Instrument Sensitivity Model

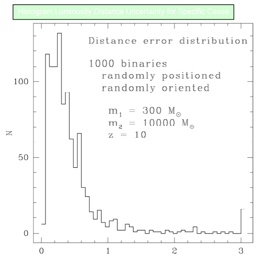


Modeled Waveforms



The histogram below left shows the uncertainty in luminosity distance for a thousand cases with a <u>single</u> LISA interferometer at *z=10*. The table below right shows the <u>median</u> performance for both distance and spin uncertainty for a range of masses at *z=10*. These calculations follow Lang and Hughes (2006, PRD, 74, 122001). Note that the performance does <u>not</u> simply follow SNR.

Histogram Luminosity Distance Uncertainty for Specific Cases



Parameter Uncertainties

M_1	M_2	D_L Uncertainty	Spin Uncertainty	SNR
1.00E+04	3.00E+02	31.90%	0.012	10.80
	1.00E+03	34.10%	0.029	18.50
	3.00E+03	43.20%	0.070	30.90
	1.00E+04	41.10%	0.115	47.90
3.00E+04	3.00E+02	28.50%	0.005	14.90
	1.00E+03	26.80%	0.008	26.40
	3.00E+03	25.00%	0.016	45.30
	1.00E+04	24.20%	0.041	79.50
1.00E+05	3.00E+02	31.70%	0.005	14.60
	1.00E+03	23.30%	0.006	27.80
	3.00E+03	20.20%	0.008	46.00
	1.00E+04	19.30%	0.020	75.00
3.00E+05	3.00E+03	22.50%	0.016	10.20

Conclusions

- Luminosity distance is the most fragile of 17 parameters. Mass, for example, is always determined more accurately, when expressed as a fractional uncertainty.
- Inclusion of spin gives a factor of 1-6 improvement. Merger and ring-down phases are not included here, and may give as much as an additional factor of 3 reduction in the uncertainty.
- The adequacy of the instrument performance can only be verified by the forward calculation. An instrument sensitivity model cannot be inverted from a collection of observation requirements.
- The LISA ScRD is now based on parameter uncertainties, providing a tighter link between science objectives and instrument sensitivity.